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Study of the Penetration of a 2 Inches Diameter YBCO Thin Film With the Travelling Magnetic Wave

W. Wang, *Student Member, IEEE*, M. Zhang, Z. Huang, Y. Zhai, Z. Zhong, F. Spaven, M. Baghdadi, and T. Coombs

Abstract—In this paper, we provide a thorough study on the penetration of a 2-in diameter YBCO thin film with the help of a travelling magnetic wave. The travelling magnetic wave is generated by a circular-type magnetic flux pump device, which is comprises of three phase windings and dc coils. We used one single hall sensor to measure the magnetic flux density 1.5 mm axially above the center of the sample. The results show that the presence of the YBCO sample had amplified the magnetic field by two times of the travelling wave in the center. After placing the hall sensor at $r = 10$ mm, we found that the magnetic field had been decreased by the presence of the sample. In order to clarify whether the flux had been bended or if there is an actual flux migration, we used a six-hall sensor array to measure the trapped field after applying the travelling wave. The measurement shows that the full penetration happens after the output voltage of the inverter $V_{ac} \geq 40$ V (maximum field 4.4 mT). The results indicate that, compared with the standing wave, the travelling wave is more efficient to help vortices penetrate into the sample center. Moreover, in practical operation of a high-temperature superconducting (HTS) flux pump, an HTS film with large width is not recommended.

Index Terms—High-temperature superconductors, magnetic flux pump, superconducting thin films, type II superconductors.

I. INTRODUCTION

THE ESSENTIAL idea of a superconducting magnetic flux pump is to apply a travelling magnetic wave to superconducting films. An ideal travelling magnetic wave should have both peak region and trough region, which provide field inhomogeneity in space, while an ideal standing magnetic wave does not have field inhomogeneity. Although both the type-I and type-II superconducting film flux pump use travelling magnetic wave as field actuator, the physics beneath these two technologies are completely different: for type-I superconducting flux pump, it requires that the crest (or trough) region of the travelling wave exceed the critical field H_C of the superconductor, thereby it acts as an electric switch and helps migrating the flux into the superconducting loop [1]; for type-II superconducting flux pump, it involves the vortex mechanics which associated with the vortex behavior under the influence of the travelling magnetic waves [2]–[4].

In order to understand the physics of a type-II superconducting flux pump, we could imagine a superconducting close loop undergo a zero-field cooling (ZFC) process. The super-

conducting close loop which made of type-II superconducting film can be single layer or multi-layer (coil). When a standing magnetic wave (homogeneous over space) is applied to the superconducting close loop, there will be an induced transport current in the loop to cancel the standing wave. If the induced current does not exceed the critical current I_C , it is sensible to simplify the loop as made of perfect conductor: as this standing wave decreases back to zero, there will be no induced current left in the loop.

However, a travelling magnetic wave can be used to avoid this problem. We had shown the different effects of travelling wave and standing wave when they are applied to a 2 inch diameter YBCO thin film [2]. The experiments show that the vortices inside the superconducting thin film are more likely to be migrated by the travelling wave rather than a standing wave. Each vortex contains a quantized magnetic fluxon, the region within the coherence length can be considered equally as the normal spot in type-I superconducting flux pump. If a massive amount of vortices have been migrated into the superconducting close loop, after switch off the applied field, there will be induced current left in the loop as in the type-I superconducting flux pump.

There are many factors which would affect the migration of vortices caused by travelling wave, such as: pinning force in the film, width of the film, inhomogeneity and amplitude of the travelling wave, *et al.* In order to help the vortices migrate into the superconducting loop, the vortices should be able to travel across the whole width of the film. In our work, it is suggested that, as the width of the film increases, it is harder for the vortices to cross. Therefore, choose a superconducting film with a sensible width is important for the efficiency of the flux pump device.

This experiment involves a circular-type magnetic flux pump (CTMFP) [5], [6] and a 2 inch diameter YBCO thin film. A six hall sensor array is placed inside the CTMFP device to measure the cross section magnetic field.

II. EXPERIMENTAL SETUP

The CTMFP had been reported in our early publications [2], [5], [6], it is the combination of the thermally actuated flux pump [3], [7], [8] and linear-type magnetic flux pump [9]. The CTMFP comprises of two CTMFP coils, while each CTMFP coil contains concentric three phase windings and a dc coil. The three phase windings are connected to a three phase inverter. During operation, the three phase windings produce an annular-shape travelling magnetic wave, with its amplitude, speed and direction are controlled by the inverter. The dc coils

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The authors are with the Electric Engineering Division, Department of Engineering, University of Cambridge, Cambridge CB3 0FA, U.K. (e-mail: ww283@cam.ac.uk).

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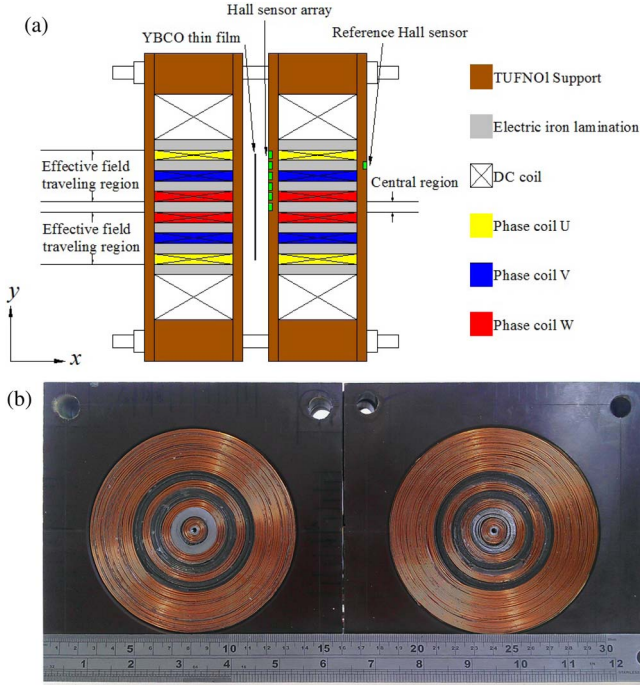


Fig. 1. Circular-type magnetic flux pump device. (a) design configuration and (b) real objects.

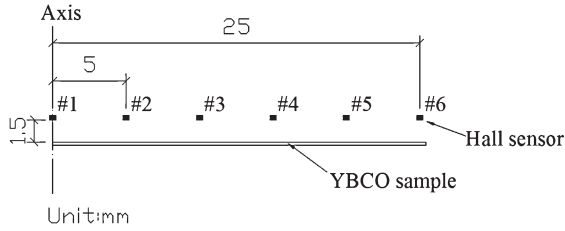


Fig. 2. Hall probes (#1-#6) and their relative position above the YBCO sample.

are connected to a dc power supply to produce a dc background field. A YBCO sample is inserted in between the CTMFP coils. The whole device is immersed in liquid nitrogen. Fig. 1 shows the configuration of the device and the real objects of the two coils.

Fig. 2 shows the relative position of the six hall probes to the YBCO thin film placed inside the CTMFP device. The hall voltage of the six hall sensors were measured by a multi-channel data acquisition card Agilent U2353A. The acquired hall voltage is calibrated into the value of magnetic flux density with a Labview program.

The superconducting sample we used in the experiment is a 2 inch diameter YBCO thin film which was provided by Ceraco Ceramic Coating GmbH, Germany. The thickness of the YBCO layer is 200 nm. More information and early experiments of this YBCO sample can be found elsewhere [2].

In this experiment, we cool the YBCO sample in zero background field, then we apply a travelling magnetic wave to the YBCO sample. In the beginning, we measure the magnetic field in the center ($r = 0$ mm) and $r = 10$ mm with or without the YBCO sample; then in order to understand the penetration of

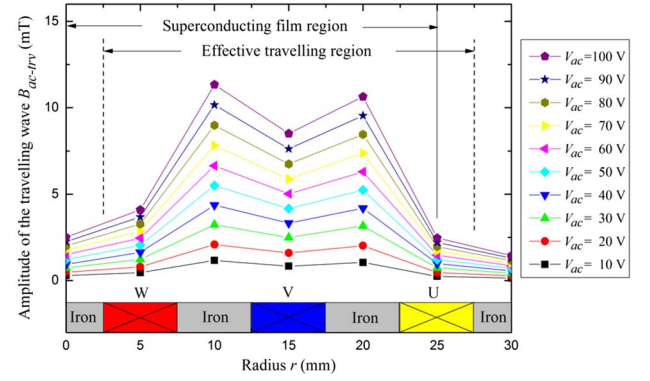


Fig. 3. Measured amplitudes of the travelling magnetic field B_x across the radius of CTMFP (without the YBCO sample).

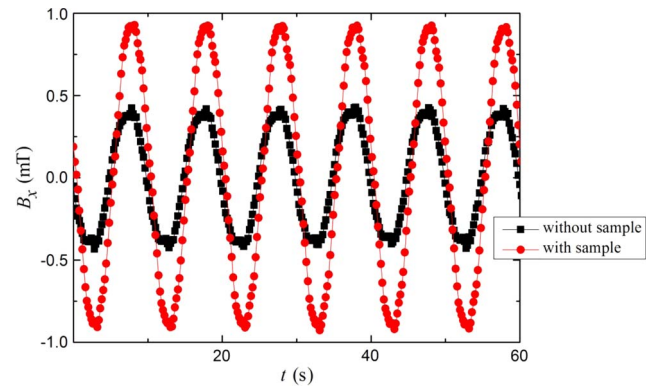


Fig. 4. Amplification of the flux density in the presence of YBCO sample in the center of the ring. The output voltage of the inverter was set as $V_{ac} = 10.0$ V, frequency $f = 0.1$ Hz.

the vortices into the sample, we use the six hall sensor array to measure the trapped field across the radius of the sample.

III. RESULTS AND DISCUSSION

A. Amplitude of the Travelling Wave

In Fig. 3, we had measured the amplitude of the travelling wave across the radius of the CTMFP. The output voltage of the inverter were set from $V_{ac} = 10$ V to 100 V with 10 V increment at each step. It is necessary to note that, Fig. 3 does not stand for the waveform. It is the maximum value of the flux density measured at each point ($r = 0, 5, 10, 15, 20, 25, 30$ mm). It is clear that there are two peaks in Fig. 3: above the iron sections at $r = 10$ mm and 20 mm.

B. Single Hall Sensor Measurement

The null dc field condition is performed under the condition of zero dc background field. Only the travelling wave is applied to the YBCO sample which is placed inside the device. The magnetic induction B_x is measured 1.5 mm above the center of the sample. We have found that the amplitude of the travelling field is amplified in the centre of the rig in the presence of a YBCO sample. An example is shown in Fig. 4 in the case of the $V_{ac} = 10.0$ V, $f = 0.1$ Hz. We denote the amplitude of the measured field without sample as B_{field} , while with sample as

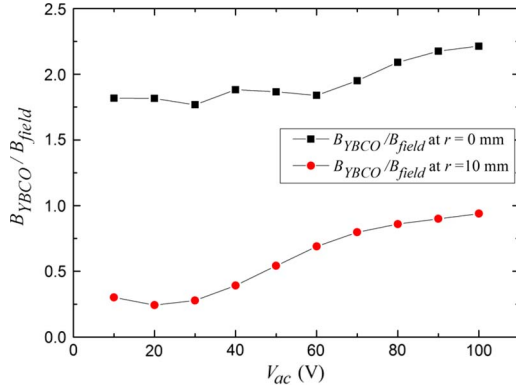


Fig. 5. Coefficient of amplification B_{YBCO}/B_{field} measured at the center and $r = 10$ mm inside the rig.

B_{YBCO} , The first curve in Fig. 5 shows the rate of amplification (B_{YBCO}/B_{field}) at the centre as a function of V_{ac} . It is clear that after inserting the YBCO sample, the field measured in the center is roughly two times of the applied field.

Superconductors are best known for shielding applied field rather than amplifying the field. Although amplification of an applied magnetic field can be achieved using magnetic lenses [10]–[13], it is also based on the fact that the superconductors expelled the flux from themselves. In order to clarify this phenomenon, we placed the hall sensor at $r = 10$ mm. The amplitude of the travelling wave at $r = 10$ mm is much bigger than the $r = 0$ mm as shown in Fig. 3. The rate of amplification (B_{YBCO}/B_{field}) is also plotted in Fig. 5. It is clear that, at $r = 10$ mm, the amplitude of the wave had been reduced in the presence of the sample. It is likely that the flux had been expelled from the high density region to the low density region, which ends up with the amplification of flux density in the center of the sample.

C. Six Hall Sensor Array Measurement

In order to observe the penetrating process of the travelling wave to the YBCO sample, we used the six hall sensor array as shown in Fig. 2 to measure the trapped field across the radius. In each experiment, after ZFC, we applied the travelling wave then switched it off at a random time. The measured magnetic induction across the radius was recorded by each hall sensor. The experiment was repeated for 20 times in order to get a profile of the trapped field.

Fig. 6 shows the experimental result for $V_{ac} = 10$ V. In Fig. 3, the maximum amplitude was measured as 1.17 mT at $r = 10$ mm. There is no trapped field measured at $r \leq 10$ mm, which indicates that there is no nett magnetization in the central region.

Fig. 7 shows the experimental result for $V_{ac} = 20$ V. In Fig. 3, the maximum amplitude was measured as 2.08 mT at $r = 10$ mm. The oscillation of the field was observed at $r = 10$ mm, which indicate that the travelling wave had penetrated at $r = 10$ mm. It is interesting to see that, in the second curve (B_{YBCO}/B_{field} at $r = 10$ mm) in Fig. 5, the point at $V_{ac} = 20$ V is the minimum point in the curve. It seems that after $V_{ac} \geq 20$ V, the flux penetrate into the region $r \leq 20$ mm,

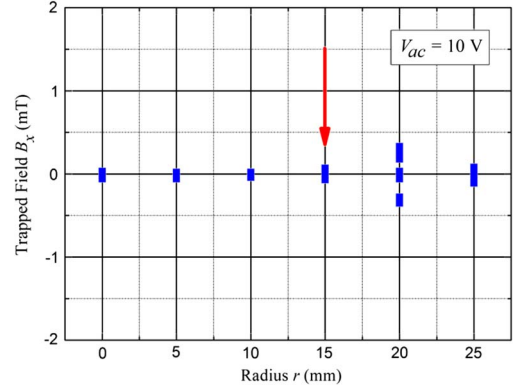


Fig. 6. Measured trapped field after applying a travelling wave for $V_{ac} = 10$ V. Each position was measured for 20 times. The oscillation was observed at $r = 15$ mm as marked by the red arrow.

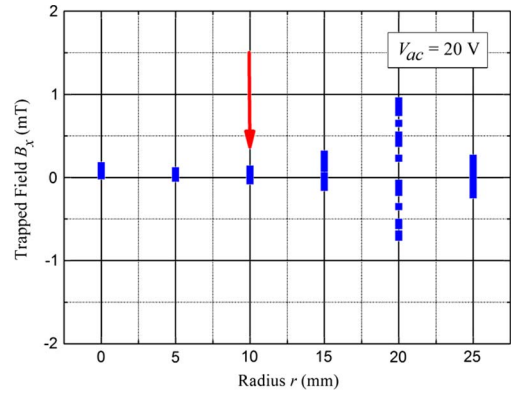


Fig. 7. Measured trapped field after applying a travelling wave for $V_{ac} = 20$ V. Each position was measured for 20 times. The oscillation was observed at $r = 10$ mm as marked by the red arrow.

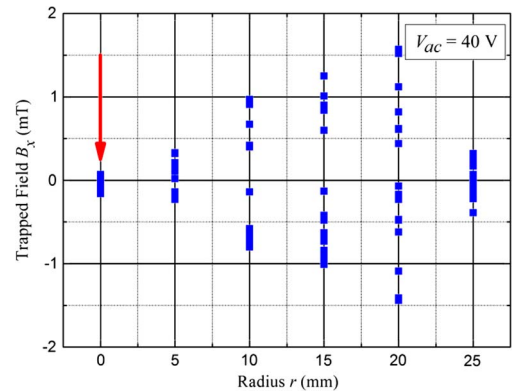


Fig. 8. Measured trapped field after applying a travelling wave for $V_{ac} = 40$ V. Each position was measured for 20 times. The oscillation was observed at $r = 0$ mm as marked by the red arrow.

which ending up with the rising of the curve B_{YBCO}/B_{field} at $r = 10$ mm in Fig. 5.

Fig. 8 shows the experimental result for $V_{ac} = 40$ V. As shown in Fig. 3, the maximum amplitude was measured as 4.36 mT at $r = 10$ mm. It is clear that, in Fig. 8, the travelling wave had fully penetrated the YBCO sample. The oscillation was observed in the center of the sample. As show in our early publication [2], for a conventional standing wave, to fully

penetrate this YBCO sample requires an amplitude of 7.0 mT. However, in Fig. 8, the sample was fully penetrated at a maximum amplitude of 4.36 mT at $r = 10$ mm. It is sensible to note that, comparing with the standing wave, travelling wave is more efficient to penetrate the sample. Also, from above study, it is clear that as the width of YBCO film increases, it is harder for the travelling wave to help the vortices to travel across the sample. However, it is possible that, this can be overcome by either increase the field inhomogeneity or increase the amplitude of the travelling wave.

IV. CONCLUSION

We had studied the penetration of a 2 inches diameter YBCO thin film with the travelling magnetic wave produced by a circular-type magnetic flux pump (CTMFP) device. We had shown that the YBCO sample is more likely to be fully penetrated by travelling wave comparing with the standing wave. Travelling magnetic wave can be used to help the vortices migrate into the superconducting close loop, which can be applied as a new method to magnetize a HTS coil. Therefore, to fully penetrate the YBCO film is the most important step in order to help the flux pump work. Our experiment suggested that, a wide YBCO film is not advisable in the practice of HTS flux pump, since it may prohibit the flux penetrate into its inner region. However, this might be overcome by either increase the field inhomogeneity or increase the amplitude of the travelling wave.

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